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(54) **IONOMER-MEMBRANE WATER  
PROCESSING METHODS**

FOREIGN PATENT DOCUMENTS

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WO WO 0022684 A2 \* 4/2000 ..... B01D 67/0088

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OTHER PUBLICATIONS

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CPC ..... C02F 1/002; C02F 1/447  
See application file for complete search history.

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

5,547,551 A \* 8/1996 Bahar ..... B01D 67/0088  
204/296  
2006/0081455 A1 \* 4/2006 Yonover ..... C02F 1/043  
202/152

(Continued)

Kelsey, et al., "Contaminant Robust Water Extraction from Lunar  
and Martian Soil for In Situ Resource Utilization—System Archi-  
tecture Development" 42nd International Conference on Environ-  
mental Systems, Jul. 15-19, 2012, San Diego, CA, 14 pages.—  
(Contaminant Robust Water Extraction.pdf).\*

Kelsey, et al., "Contaminant Robust Water Extraction from Lunar  
and Martian Soil for In Situ Resource Utilization—System Testing."  
American Institute of Aeronautics and Astronautics, 15 pages.—  
(Contaminant Robust Water Extraction—System Testing.pdf).\*

(Continued)

*Primary Examiner* — Krishnan S Menon

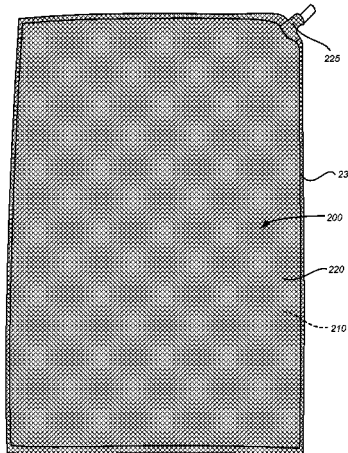
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(57) **ABSTRACT**

This disclosure provides water processing apparatuses, sys-  
tems, and methods for recovering water from wastewater  
such as urine. The water processing apparatuses, systems,  
and methods can utilize membrane technology for extracting  
purified water in a single step. A containment unit can  
include an ionomer membrane, such as Nafion®, over a  
hydrophobic microporous membrane, such as polytetraflu-  
oroethylene (PTFE). The containment unit can be filled with  
wastewater, and the hydrophobic microporous membrane  
can be impermeable to liquids and solids of the wastewater  
but permeable to gases and vapors of the wastewater, and the  
ionomer membrane can be permeable to water vapor but  
impermeable to one or more contaminants of the gases and  
vapors. The containment unit can be exposed to a dry purge  
gas to maintain a water vapor partial pressure differential to  
drive permeation of the water vapor, and the water vapor can  
be collected and processed into potable water.

**20 Claims, 10 Drawing Sheets**



**Related U.S. Application Data**

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(51) **Int. Cl.**

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*C02F 1/44* (2006.01)

*C02F 103/08* (2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2009/0181276	A1 *	7/2009	Beutel .....	H01M 4/8825 429/480
2009/0266048	A1 *	10/2009	Schwarz .....	B01D 39/1692 60/39.092
2010/0096317	A1 *	4/2010	Morita .....	B01D 63/081 210/321.84
2012/0255897	A1 *	10/2012	Lu .....	B01D 69/02 210/321.6

OTHER PUBLICATIONS

Kelsey, et al., "Development of Ionomer-membrane Water Processor (IWP) technology for water recovery from urine." 44th International Conference on Environmental Systems, Jul. 13-17, 2014, Tucson, AZ, 23 pages.—(Development of Ionomer-membrane Water Processor.pdf).\*

Kelsey, et al., "Employing ionomer-based membrane pair technology to extract water from urine." 42nd International Conference on Environmental Systems, Jul. 15-19, 2012, San Diego, CA, 20 pages.—(Employing ionomer-based membrane pair technology.pdf).\*

Kelsey, et al., "Inspiration Mars ETDU Water Management System Test Results." 44 International Conference on Environmental Systems, Jul. 13-17, 2012, Tucson, AZ, 28 pages.—(Inspiration Mars ETDU.pdf).\*

Kelsey, et al., "Purifying Water Mined from Asteroids for In Situ Resource Utilization." Paragon Space Development Corporation, 23 pages.—(Purifying Water Mined from Asteroids.pdf).\*

\* cited by examiner

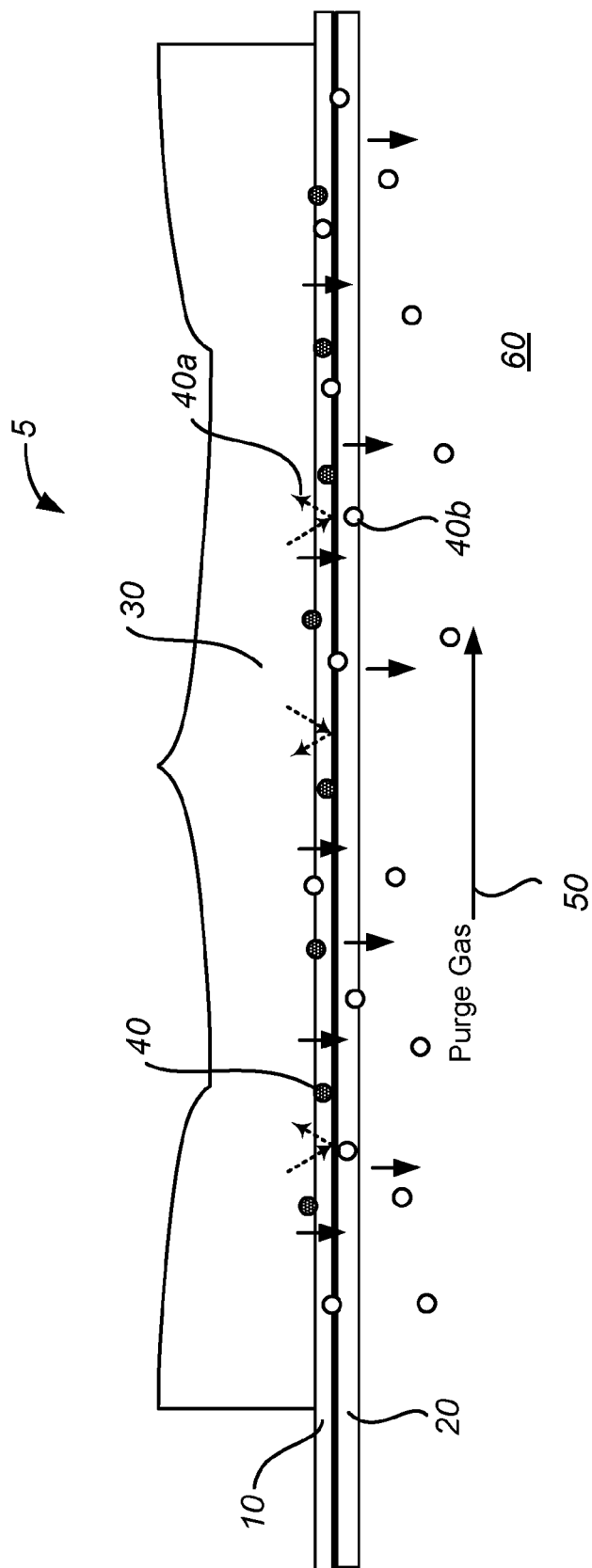
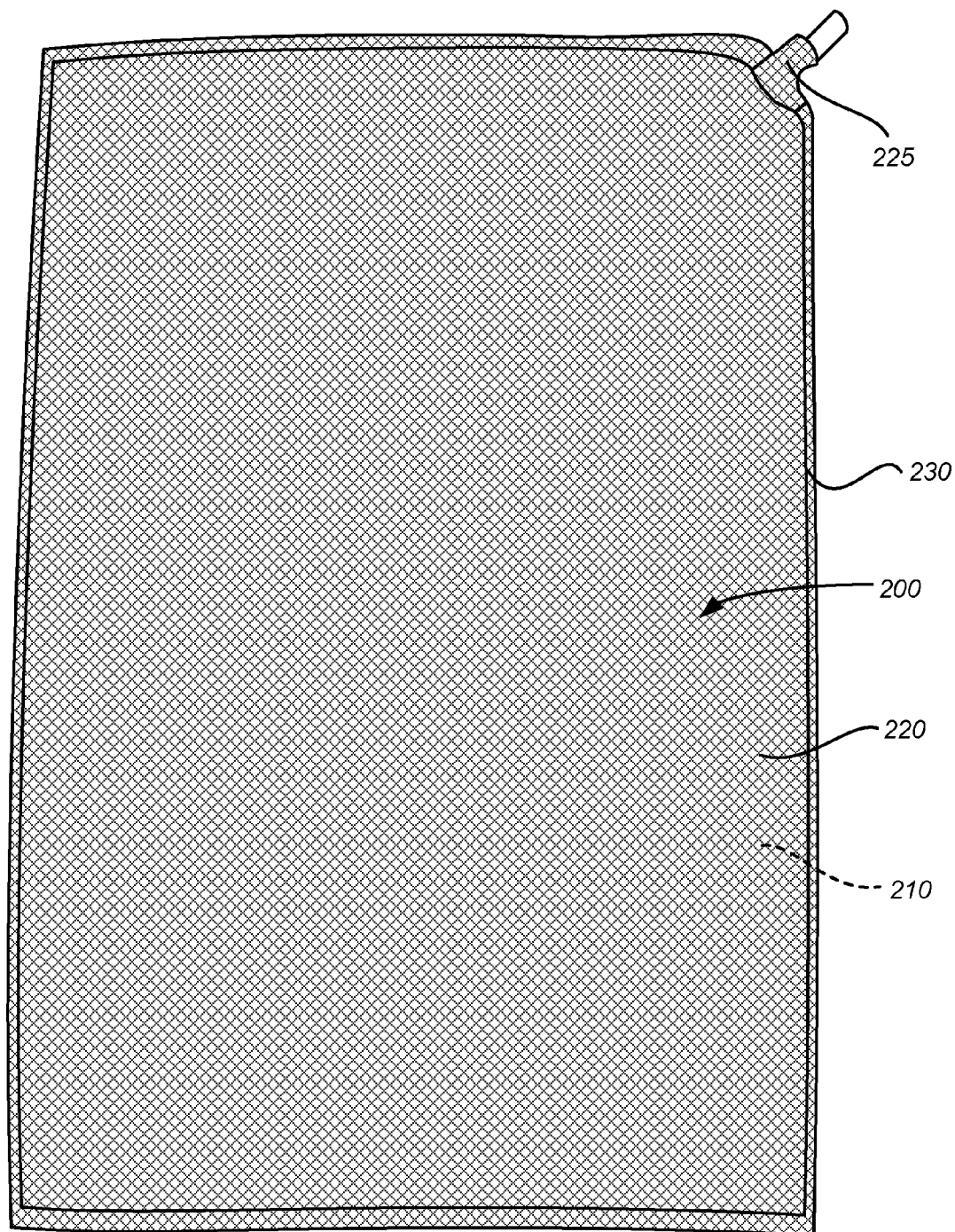


FIG. 1

**FIG. 2A**

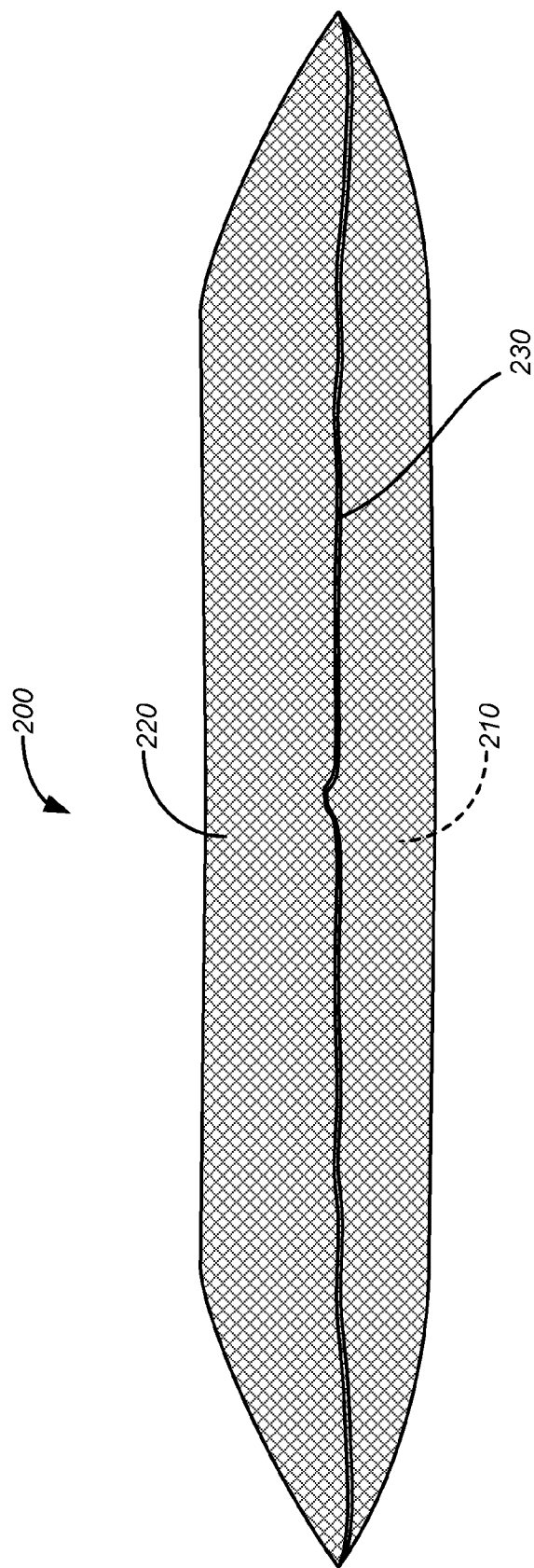


FIG. 2B

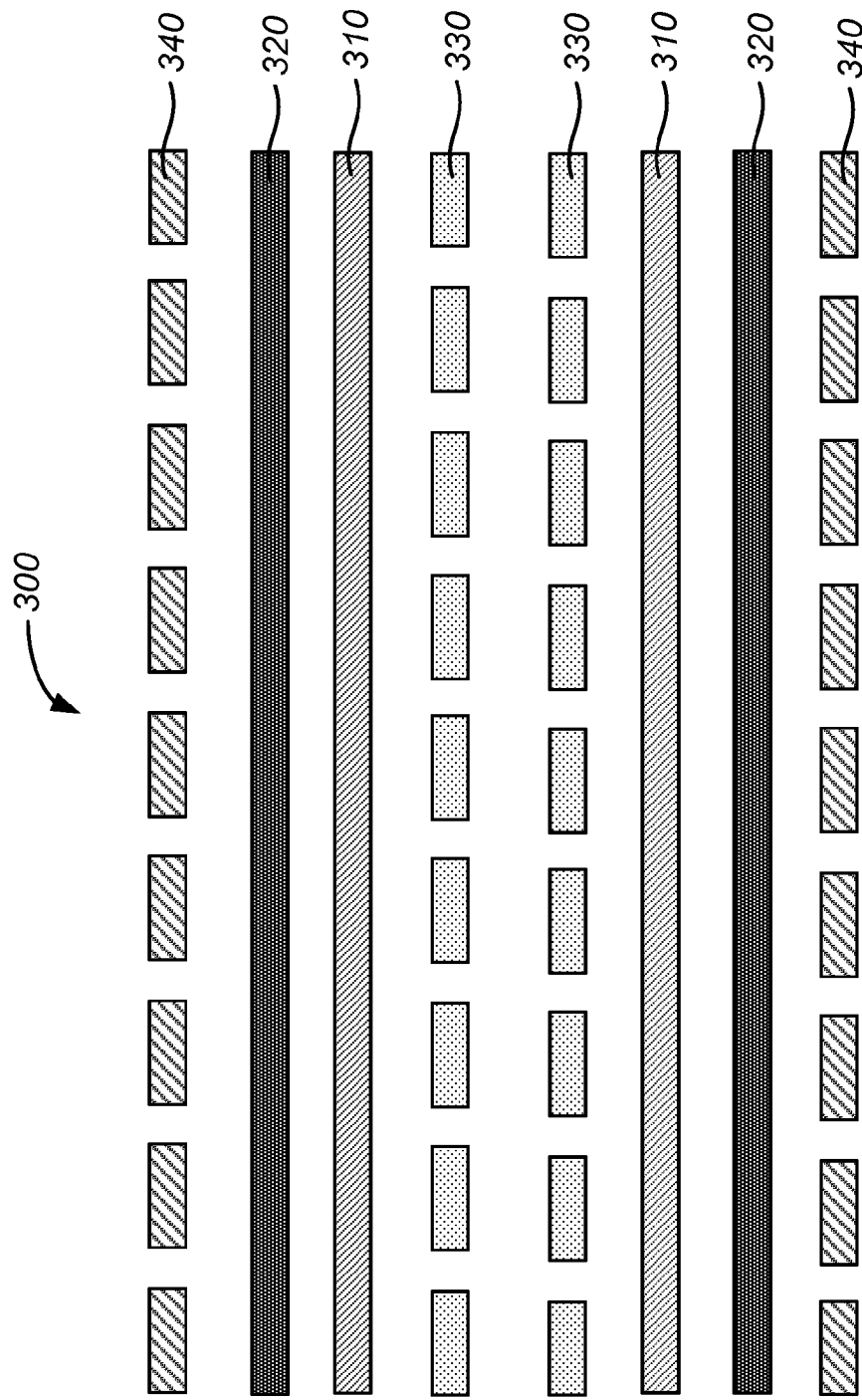


FIG. 3

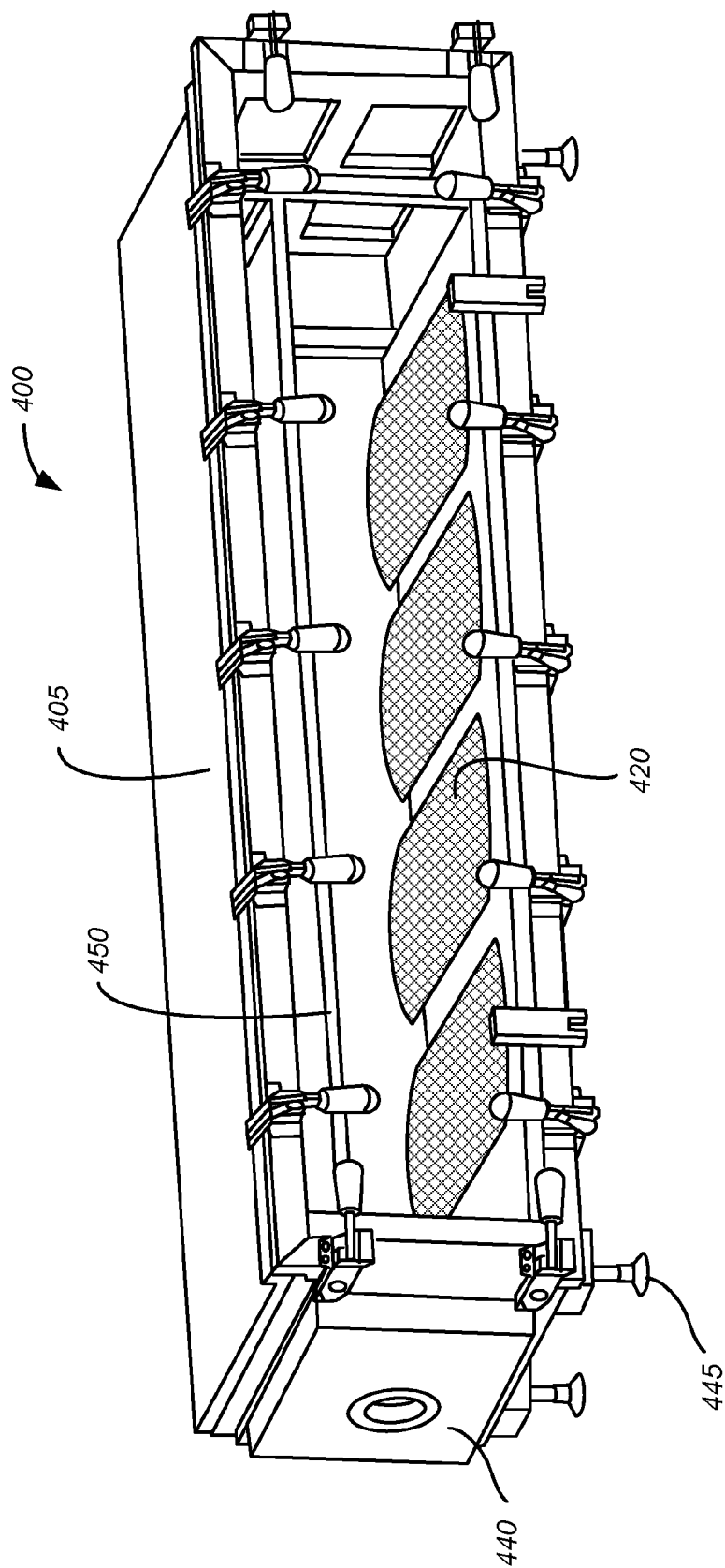


FIG. 4A

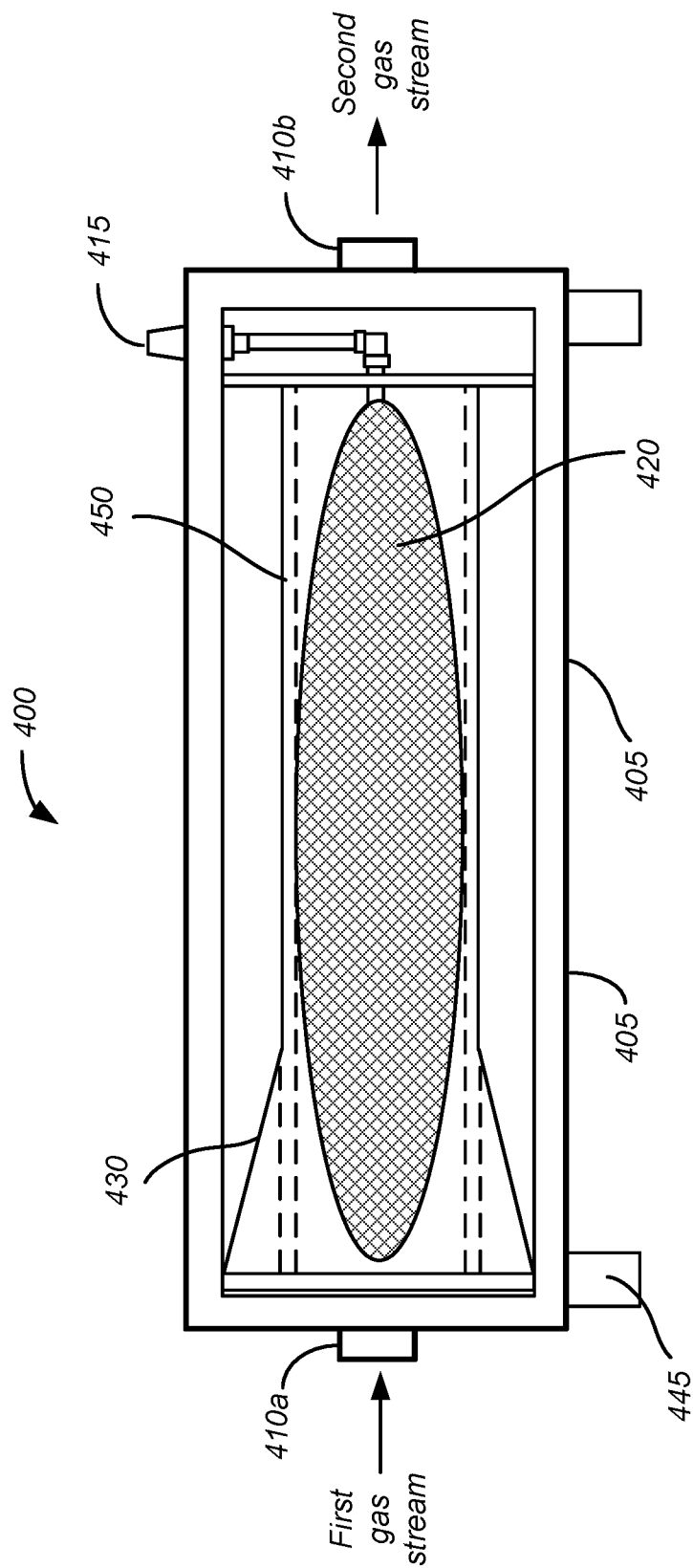


FIG. 4B



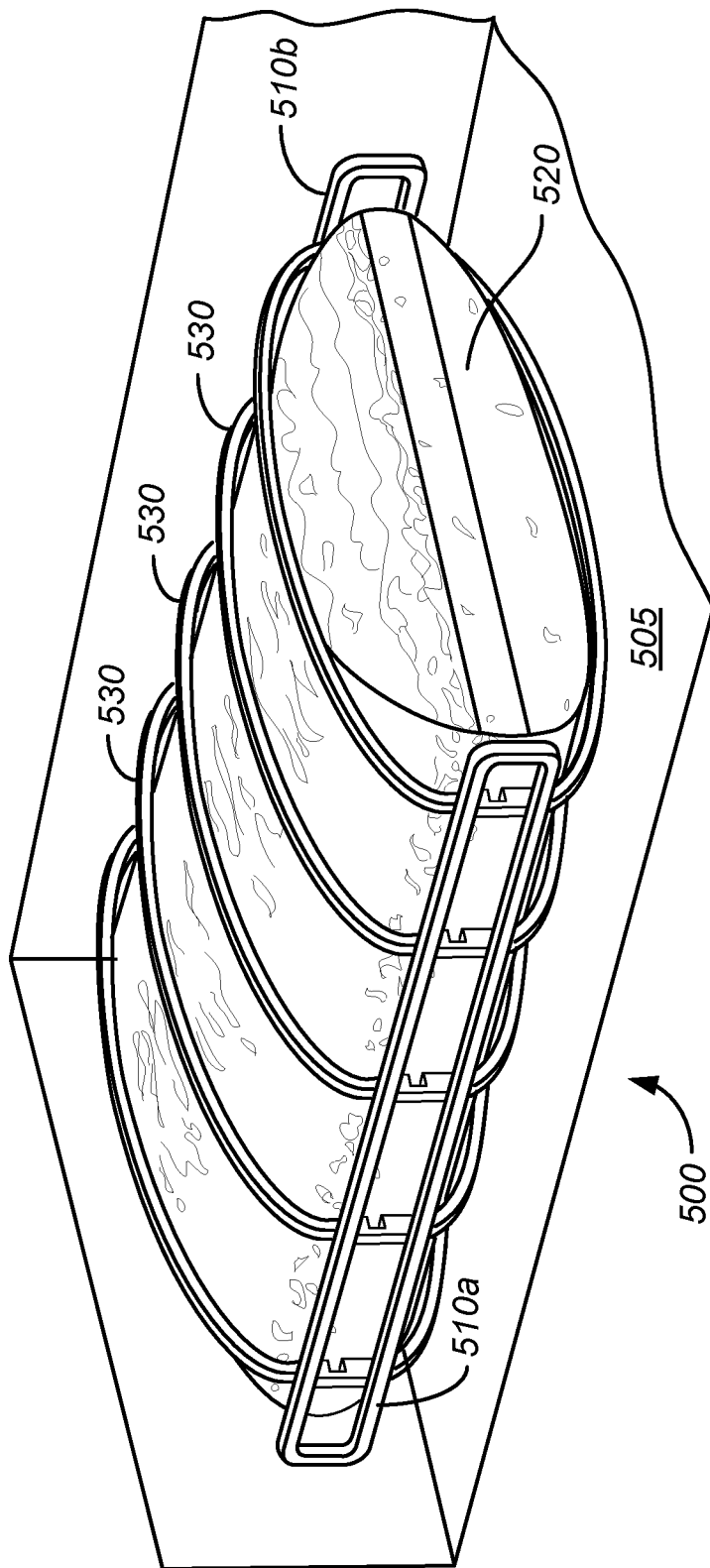


FIG. 5

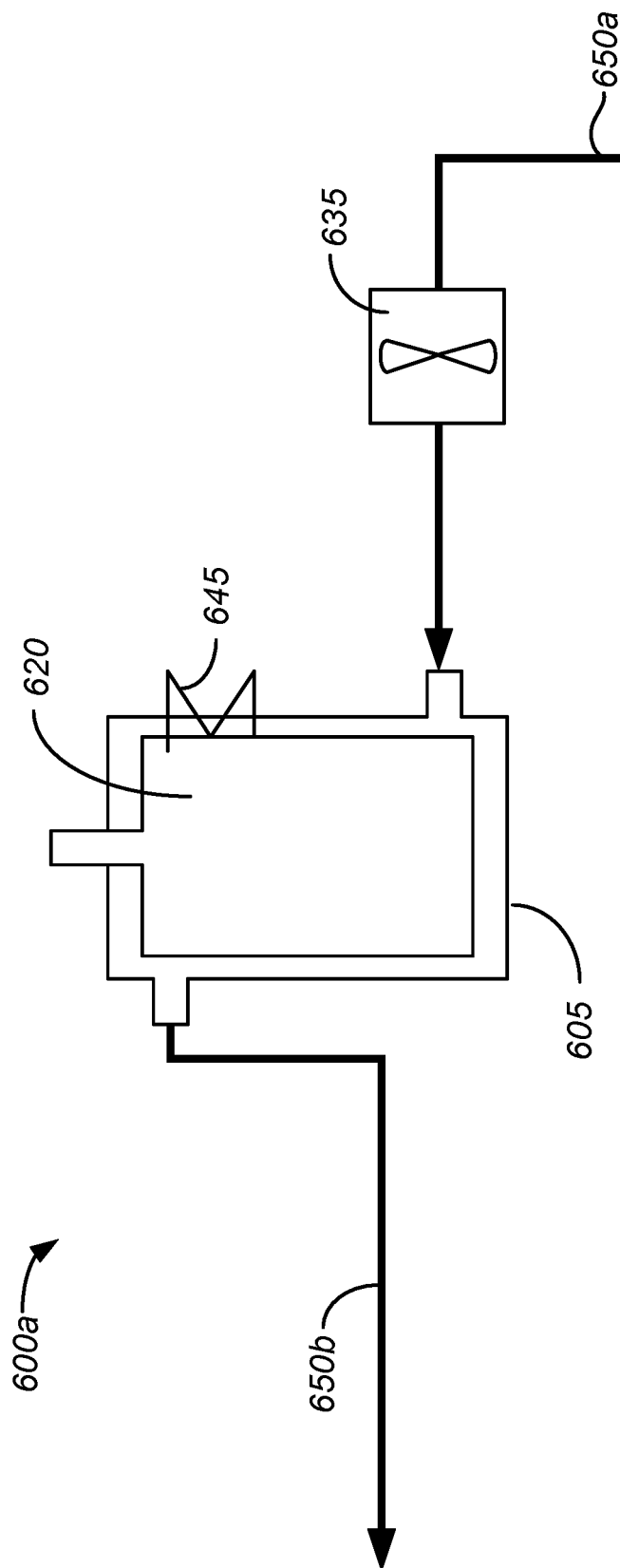


FIG. 6A

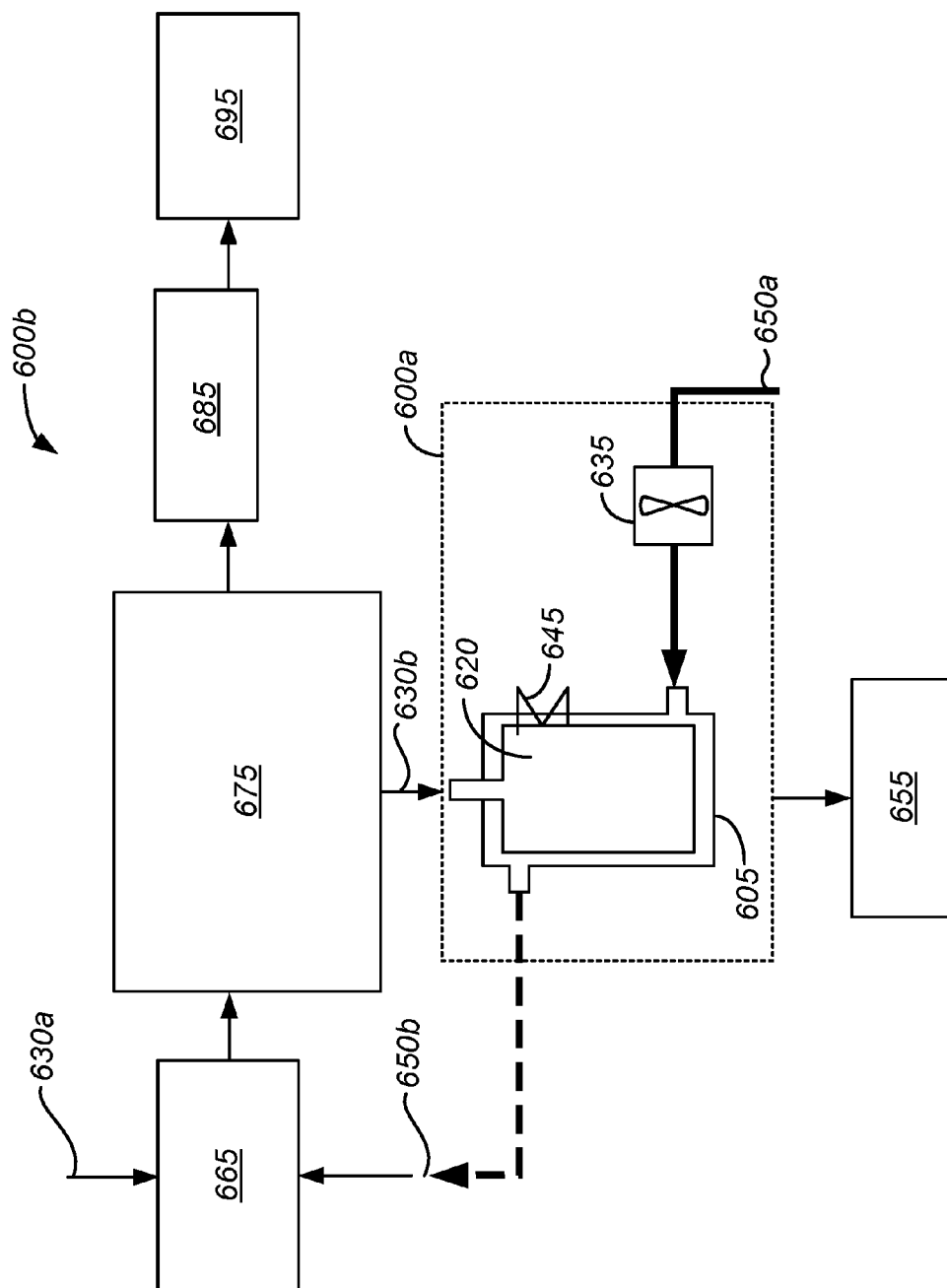


FIG. 6B

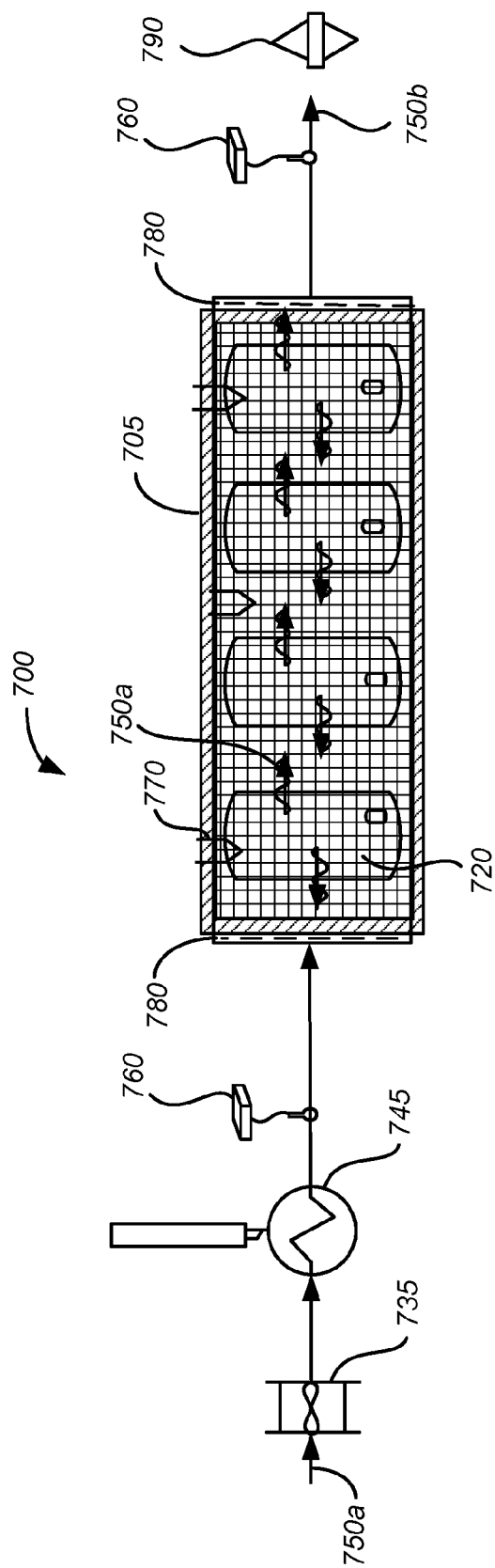


FIG. 7

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# IONOMER-MEMBRANE WATER PROCESSING METHODS

## PRIORITY CLAIM

This application is a continuation of U.S. patent application Ser. No. 14/609,735, filed Jan. 30, 2015, entitled “IONOMER-MEMBRANE WATER PROCESSING APPARATUS” which claims priority to U.S. Provisional Patent Application No. 61/934,382 filed Jan. 31, 2014 and entitled “Contaminant Robust In Situ Water Extractor Systems,” which is hereby incorporated by reference in its entirety and for all purposes.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Some embodiments of this invention were developed with United States Government Support under NNX11CB47C, NNX11CH41P, and NNX12CA10C awarded by The National Aeronautics and Space Administration (NASA). The Government has certain rights in the invention.

## TECHNICAL FIELD

This disclosure relates to extracting water from wastewater, and more particularly to extracting water from urine or brine using ionomer-microporous membrane technology for liquid and gas separation.

## BACKGROUND

One of the most important resources for human support is potable water. Large populations in our world lack access to potable water and access to adequate sanitation. In addition, potable water is important for long-term human missions in space, where such water may be vital for consumption, hygiene, and maintenance. Since supplies of potable water may not be readily available, water reclamation to generate potable water from wastewater is essential. Sources of wastewater in long-term space missions can consist of hygiene water, laundry water, humidity condensate, brines, and human waste (e.g., urine). Due to the high cost of delivering supplies to space, recovery of potable water from wastewater may be critical to life support of crew members. Long duration space missions to the moon, Mars, and near-Earth asteroids may be mass-constrained and may require robust and reliable life support hardware. Closing the water loop on long duration space missions can be crucial to reducing mission mass, cost, and logistics support for orbiting facilities and planetary spacecraft.

Water recovery from wastewater is not only important in space applications, but can also be important in terrestrial applications. Such terrestrial applications of water recovery can include water recycling in arid regions, water treatment for disaster relief, greywater recycling onboard ships, and water recycling at long-term military outposts, ships, and submarines.

One type of wastewater for closing the water loop can include urine. On the International Space Station (ISS), urine may be stabilized using pretreatment chemicals, such as chromium trioxide and sulfuric acid, at a waste collection system. Typically, water can be recovered from the pretreated urine using a Vapor Compression Distillation (VCD) system. The VCD system is capable of recovering about 75% of water from the pretreated urine. However, the VCD system is very complex and uses several moving parts.

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Furthermore, the VCD system produces brine that requires further processing for water recovery.

Due to the VCD system's complexity and reduced capacity, membrane technology has been developed to simplify water purification systems. One such membrane-based strategy is reverse osmosis membrane technology and another such membrane-based strategy is forward osmosis membrane technology. While both reverse osmosis membranes and forward osmosis membranes may be effective in limiting surfactants, both are unable to reject urea, which is a small, uncharged contaminant molecule typically found in urine. As a result, such membranes may be supplemented with a second process capable of filtering out urea. Osmotic distillation and membrane distillation technology may be used to reject urea, but are not effective in limiting low-surface tension fluids, such as surfactants. When integrated together, this leads to the complexity and costs of water recovery from wastewater. Also, having to use different systems to treat different streams of wastewater can present problems from a mass, power, cost, logistics, and volume perspective. A single practical process that is capable of extracting purified water from urine in a single step may be beneficial in closing the water loop.

## SUMMARY

The systems, methods and devices of this disclosure each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein.

One innovative aspect of the subject matter described in this disclosure can be implemented in a water processing apparatus for treating wastewater. The water processing apparatus can include a containment unit for holding the wastewater, where the containment unit includes a first layer forming the interior of the containment unit and a second layer over the first layer and exposed to the ambient environment. The first layer includes a hydrophobic microporous membrane, and the second layer includes an ionomer membrane.

In some implementations, the ionomer membrane includes Nafion®. In some implementations, the hydrophobic microporous membrane includes polytetrafluoroethylene (PTFE). In some implementations, the first layer has a first surface area and the second layer has a second surface area, the ratio of the first surface area to the second surface area being between about 1.25:1 and about 1:1.25. In some implementations, the first layer is impermeable to liquids and solids of the wastewater but permeable to gases and vapors of the wastewater, and the second layer is permeable to water vapor but impermeable to one or more contaminants of the gases and vapors.

Another innovative aspect of the subject matter described in this disclosure can be implemented in a water recovery system for treating wastewater and recovering water. The water recovery system can include a housing structure and one or more containment units for holding wastewater and supported in the housing structure. The housing structure can include a gas inlet for receiving a first gas stream into the housing structure and a gas outlet for delivering a second gas stream out of the housing structure, where the second gas stream includes water. Each of the containment units can include a first layer forming the interior of the containment unit and a second layer over the first layer and exposed to the ambient environment of the housing structure. The first layer can include a hydrophobic microporous membrane and the second layer can include an ionomer membrane.

In some implementations, the ionomer membrane includes Nafion®. In some implementations, the hydrophobic microporous membrane includes PTFE. In some implementations, the first layer has a first surface area and the second layer has a second surface area, where the ratio of the first surface area to the second surface area is approximately 1:1. In some implementations, water vapor partial pressure inside the housing structure is less than the water vapor partial pressure inside the containment units. In some implementations, the relative humidity of the second gas stream is greater than the relative humidity of the first gas stream. In some implementations, the first layer is impermeable to liquids and solids of the wastewater but permeable to gases and vapors of the wastewater, and the second layer is permeable to water vapor but impermeable to one or more contaminants of the gases and vapors.

Details of one or more implementations of the subject matter described in this disclosure are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the drawings and the claims. Note that the relative dimensions of the following figures may not be drawn to scale.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic diagram illustrating an example water processing apparatus including an ionomer and hydrophobic microporous membrane pair for extracting water from wastewater.

FIG. 2A show a top plan view of an example containment unit for holding and treating wastewater for water recovery.

FIG. 2B shows a side view of the containment unit in FIG. 2A for holding and treating wastewater for water recovery.

FIG. 3 shows a schematic of various layers in an example containment unit configured to hold and treat wastewater for water recovery.

FIG. 4A shows an example water processing apparatus including a rigid housing structure supporting containment units configured to hold and treat wastewater for water recovery.

FIG. 4B shows a schematic of the example water processing apparatus of FIG. 4A including a rigid housing structure supporting a containment unit configured to hold and treat wastewater for water recovery.

FIG. 5 shows another example water processing apparatus including a flexible housing structure supporting a containment unit configured to hold and treat wastewater for water recovery.

FIG. 6A shows an example schematic diagram illustrating a water processing apparatus for treating wastewater.

FIG. 6B shows an example schematic diagram illustrating the water processing apparatus of FIG. 6A integrated in a water recovery system.

FIG. 7 shows a schematic diagram illustrating a water recovery system having containment units configured to hold and treat wastewater.

Like reference numbers and designations in the various drawings indicate like elements.

#### DETAILED DESCRIPTION

To reclaim water from wastewater, a water processing apparatus can be provided that can extract purified water in a single step. The extracted water can meet water quality standards, such as having a limited amount of total organic carbon, total inorganic carbon, total dissolved solids, ammo-

nium, urea, methanol, ethanol, propylene glycol, acetate, sulfate, formate, and other contaminants. The amount of extracted water from the wastewater can also be significant. For example, the water processing apparatus can be capable of extracting over 75% of the water from the wastewater. For example, the water processing apparatus may be capable of extracting equal to or greater than about 85% of the water from brine, and extracting equal to or greater than about 98% of the water from urine. The water processing apparatus can be capable of using limited power and limit the use of consumable components.

Wastewater can come from a variety of sources, including but not limited to humidity condensate from air conditioning systems, hygiene water, seawater, polluted water, greywater, brine, and urine. Human urine can include several different inorganic salts, urea, organic ammonium salts, and other organic compounds. Human urine also includes water, the percentage of which can vary from person to person. Typical samples of urine can be augmented to match that of a typical crew member of the ISS, where the percentage of non-water compounds can be less than 20% and the percentage of water can be greater than 80% in terms of mass fraction of the urine. For example, pretreated, augmented urine can include 6.06% of non-water compounds and 93.94% of water, where the urine can be pretreated with sulfuric acid and chromium trioxide to prevent bacterial and mold growth and trap ammonium in solution as non-volatile ammonium ions. In some implementations, water recovery techniques may be utilized to purify water from urine. In some other implementations, water recovery techniques may be utilized to purify water from brine. For example, the brine can be a form of concentrated urine, where pretreated urine can be processed in a primary water processor to become brine. Then the brine can be further processed by the water processing apparatus of the present disclosure. The effectiveness of the present disclosure can be evaluated in terms of the amount of water recovery from the wastewater and the product water purity.

The present disclosure provides for wastewater processing using membrane technology. FIG. 1 shows a schematic diagram illustrating an example water processing apparatus including an ionomer and hydrophobic microporous membrane pair for extracting water from wastewater. A water processing apparatus 5 for extracting water from wastewater can include a first layer 10 over a second layer 20. The first layer 10 can include a hydrophobic microporous membrane and the second layer 20 can include an ionomer membrane. The first layer 10 and the second layer 20 can form an ionomer-microporous membrane pair that can be used in water recovery processes for a variety of applications, including space and terrestrial applications. The first layer 10 can be impermeable to liquids and solids of the wastewater 30 but permeable to gases and vapors 40 of the wastewater 30. The second layer 20 can be permeable to water vapor 40b but impermeable to one or more contaminants 40a of the gases and vapors 40.

In some implementations, the hydrophobic microporous membrane of the first layer 10 can include polytetrafluoroethylene (PTFE) or, more specifically, expanded PTFE (ePTFE). PTFE, sometimes referred to as "Teflon," can serve as a hydrophobic microporous membrane that prevents liquid wastewater 30 from coming into contact with the second layer 20. The PTFE in the first layer 10 may prevent liquid wastewater 30 from passing but may permit gases and vapors 40 to pass through. PTFE is hydrophobic and does not allow any liquid to pass through its pores without significant backpressure. In addition, PTFE has high tem-

perature limits and will generally not degrade at temperatures below about 250° C. PTFE is also very chemically inert and highly resistant to corrosion. In some implementations, PTFE is able to handle heated, highly concentrated brine without any chemical corrosion or with minimal chemical corrosion. In some implementations, the PTFE can be derived from Teflon manufactured by General Electric of Fairfield, Conn. An example of PTFE can be derived from fabric of the product name eVent®, which can be manufactured by the BHA Group, a subsidiary of General Electric. The eVent® product is commercially available in different porosities and thicknesses, which can affect permeation rates.

In some implementations, the ionomer membrane of the second layer 20 can include a sulfonated perfluorinated ionomer, such as Nafion®. The ionomer membrane of the second layer 20 serves as a chemically-selective membrane that allow compounds that bind to the sulfonic acid groups to readily permeate through the second layer 20, including water. The ionomer membrane is a chemically-sensitive membrane in that it selectively passes water through the ionomer membrane based on chemical affinity. Rather than selectively removing water or other gases based on molecular size, the ionomer membrane can remove water and other gases based on chemical affinity. For example, the ionomer membrane can remove water and other gases based on their chemical affinity for sulfonic acid groups.

Nafion® is a copolymer of tetrafluoroethylene and perfluoro-3,6-dioxo-4-methyl-7-octene-sulfonic acid. It is an inert fluorocarbon polymer with ionic channels of sulfonic acid groups scattered throughout. Nafion® is highly resistant to chemical attack, as only alkali metals such as sodium are known to degrade Nafion® under normal temperatures and pressures. In fact, strong acids may be used to regenerate Nafion® if it has been exposed to solutions containing cations. Because of its inertness, Nafion® can be safely disposed in landfills. Nafion® does not burn in ambient air and is more flame-resistant than most other plastics, with a limiting oxygen index of 95%. Nafion® sheets are commercially available through Ion Power, Inc., which is a distributor of Nafion® under E. I. du Pont de Nemours and Company of Wilmington, Del. Different thicknesses of Nafion® are commercially available, which can affect the permeation rates.

Nafion® includes a bulk fluorocarbon matrix with exposed sulfonic acid groups immobilized in the bulk fluorocarbon matrix. Unlike the fluorocarbon matrix, the sulfonic acid groups do not participate in chemical reactions. As a result, the sulfonic acid groups provide several important properties to Nafion®. First, Nafion® functions as an acid catalyst due to the strongly acidic properties of the sulfonic acid group. Second, Nafion® functions as an ion exchange resin when exposed to liquid solutions. Third, Nafion® can readily absorb water, from the vapor phase or the liquid phase. Each of the sulfonic acid groups can absorb up to 13 molecules of water. The sulfonic acid groups can form ionic channels through the fluorocarbon polymer, and water can be easily transported through these channels. Thus, Nafion® can serve as a selective, semi-permeable membrane to water vapor. In some implementations, the Nafion® of the second layer 20 can be provided as a sheet or sheets. In some implementations, the Nafion® can be solution-casted onto the first layer 10. In some implementations, the Nafion® of the second layer 20 can be provided as tubes that can form Nafion® tube walls. Nafion® tubes may be commercially available through Perma Pure LLC of Toms River, N.J.

Nafion® can serve as a selective, semi-permeable membrane to water vapor for water purification because the sulfonic acid groups can pass water while rejecting other

compounds, making it possible to separate water from a contaminated source. The fact that Nafion® acts as an ion exchange resin when exposed to liquids implies that Nafion® is more effective processing gases rather than liquid solutions. Liquid solutions containing cations can reduce the effectiveness of the permeability of Nafion® by supplanting the hydrogen ions of sulfonic acid groups with the solution cations. Given these properties, the pores in the PTFE of the first layer 10 selectively prevent liquid wastewater 30 from passing through, but allow gases and vapors 40 to pass. As a result, liquid wastewater 30 does not reach the Nafion® of the second layer 20. When gases and vapors 40 encounter the Nafion® of the second layer 20, the Nafion® selectively permeates water vapor 40b while blocking or otherwise “retaining” the volatiles 40a of other compounds. As used herein, “retaining” means that the volatiles of the compounds do not pass through the membrane of the second layer 20. The retained volatiles 40a can include contaminants such as ammonia, alkanes, alkenes, alkynes, double and triple-bonded organic compounds, and benzene, among others. Some of the retained volatiles 40a may be retained by converting into another compound, where some compounds may be susceptible to acid catalysis, for example.

In operation, the wastewater 30 can be in contact with the first layer 10. In some implementations, the wastewater 30 can include urine, hygiene water, humidity condensate, seawater, greywater, brine, or other contaminant solution. In some implementations, the wastewater 30 is urine. In some other implementations, the wastewater 30 is brine. The brine can be a form of concentrated urine, where the brine can be received after processing urine by a primary water processor. The urine may be pretreated to prevent bacterial and mold growth and trap ammonia in solution as non-volatile ammonium ions. The first layer 10 may limit solid and liquid solution of the wastewater 30 from passing through, but may permit vapors and gases 40 to pass through.

The second layer 20 may be directly disposed, positioned, formed, or otherwise placed on the first layer 10. In some implementations, the first layer 10 and the second layer 20 are in contact with one another. In other words, the first layer 10 and the second layer 20 can be sandwiched together. This can form an ionomer membrane and hydrophobic microporous membrane pair. In some implementations, the second layer 20 is exposed to an ambient environment 60. Of the vapors and gases 40 to pass through the first layer 10, the second layer 20 can block or substantially retain volatiles 40a that are unable to permeate through the second layer 20. The rate of loss of some of the volatiles 40a can depend on how readily the volatiles 40a will undergo acid catalysis. Table 1 summarizes a list of chemicals that are retained or at least partially retained by Nafion®.

TABLE 1

Chemical	Retention with Nafion ®
Ammonia	Variable losses in the form of ammonium hydroxide
Ammonium Hydroxide	Over 90% loss
Acetaldehyde	Retained
Acetic Acid	Over 90% loss due to acid catalysis
Acetone	Over 90% loss
Acetonitrile	75% loss
Acrolein	Variable losses
Anisole	Retained
Benzaldehyde	75% loss
Benzene	Retained
Benzonitrile	50% loss

TABLE 1-continued

Chemical	Retention with Nafion®
Boron Trifluoride	Retained
Bromofom	Retained
Carbon Dioxide	Retained
Carbon Disulfide	Retained
Carbon Monoxide	Retained
Chlorine	Retained
Chloroethane	Retained
Chloroform	Retained
Crotonaldehyde	Over 90% loss
Cumene	Retained
Diacetyl	Over 90% loss
Diethyl Carbitol	Variable losses
Dimethylformamide	Over 90% loss
Dimethylacetamide	Over 90% loss
Dioxane	Over 90% loss
DMS	Retained
DMSO	Over 90% loss
Ethane	Retained
Ethanol	Over 90% loss
Ethyl Acetate	15% loss
Ethyl Amyl Ketone	20% loss
Ethyl Benzene	Retained
Ethyl Ether	Over 90% loss
Ethylene	Retained
Ethylene Oxide	50% loss
Fluorine	Retained
Fluorobenzene	Retained
Formaldehyde	Retained
Formic Acid	Variable loss
Helium	Retained
Heptane	Retained
Hexane	Retained
Hydrogen	Retained
Hydrogen Chloride	Retained with high purge
Hydrogen Cyanide	Retained
Hydrogen Fluoride	Retained
Hydrogen Sulfide	Retained
Isopropyl Benzene	Retained
Isobutyl Acetate	Over 90% loss
Isovaleric Acid	Variable losses
MEK	Over 90% loss
Mesitylene	Retained
Methane	Retained
Methanol	Over 90% loss
Methyl Acetate	Retained
Methyl Bromide	Retained
Methyl Chloride	Retained
Methyl Isobutyl Ketone	Over 90% loss
Methyl Methacrylate	Retained
Methyl Nitrate	Variable losses
Methyl Sulfide	Retained
Nitrobenzene	30% loss
Nitrogen	Retained
Nitrogen Dioxide	Retained
Octane	Retained
Oxygen	Retained
Ozone	Retained
Propane	Retained
Phosgene	Retained
Propionic Acid	Variable losses
Propylene	Retained
Propylene Oxide	25% loss
Pyridine	Retained
Sulfur Dioxide	Retained
Tetrahydrofuran	Over 90% loss
Thiosinamine	Over 90% loss
Toulene	Retained
Trichloroethene	Retained
Water	Over 90% loss
Xylene	Retained

The Nafion® of the second layer 20 may block or substantially retain volatiles 40a that come from the wastewater 30. The Nafion® of the second layer may allow other vapors and gases 40 to pass, including water vapor 40b. Of note, alcohols, ammonium hydroxide, primary amines, and

secondary amines may selectively permeate through the Nafion® of the second layer 20, driven by their vapor pressure gradients. Even though some volatiles 40a may pass through both membranes, the contamination of the permeated water vapor 40b may be minimal based on total organic carbon (TOC), ammonia, ammonium, and pH measurements.

The water vapor 40b can pass through the second layer 20 by being driven by a partial pressure differential. In some implementations, the water vapor partial pressure in the ambient environment 60 is less than the water vapor partial pressure inside the second layer 20. Water molecules of the water vapor 40b can bind to the sulfonic acid groups of the Nafion® in the second layer 20, and then pass through by the partial pressure differential. Rapid transfer through the second layer 20 can keep the partial pressure between the first layer 10 and the second layer 20 low, allowing for high diffusion through the first layer 10.

The water vapor partial pressure differential is the driving force for permeation of water vapor 40b. The larger the differential, the higher the potential for permeation. The water vapor partial pressure differential can be maintained by a dry sweep gas flowing over the second layer 20. As illustrated in the example in FIG. 1, a purge gas 50 can flow through the ambient environment 60 to sweep the water vapor 40b. The purge gas 50 can flow across the surface of the second layer 20 to pick up the water vapor 40b and transport the water vapor 40b. In some implementations, the water vapor 40b can be transported to a condenser (not shown). In some implementations, the purge gas 50 can include air, such as room air delivered by a fan or compressor. However, it is understood that the purge gas 50 can include any gas that has as water vapor partial pressure that is lower than the water vapor partial pressure inside the second layer 20. For example, the purge gas 50 can include one or more of nitrogen (N<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), hydrogen (H<sub>2</sub>), and inert gas.

The flow rate, temperature, and relative humidity of the purge gas 50 can be adjusted to increase the permeation of the water vapor 40b from the wastewater 30 to the ambient environment 60. For example, increasing the flow rate of the purge gas 50 can increase the permeation of the water vapor 40b and prevent saturation. Increasing the temperature can increase the permeation of the water vapor 40b to counteract the effects of evaporative cooling. Decreasing the relative humidity of the purge gas 50 can increase the permeation rate of water vapor 40b.

The permeation of water vapor 40b may also be affected by other factors. In some implementations, the level of hydration of the Nafion®, the phase of water on the side of the wastewater 30, interfacial transport, surface area ratio of the first layer 10 to the second layer 20, membrane thicknesses, and porosity of the PTFE membrane can affect the permeation of water vapor 40b.

With respect to surface area ratio of the first layer 10 to the second layer 20, high permeation rates can be achieved when the first layer 10 has a similar surface area as the second layer 20. For example, comparative permeation rates through PTFE and Nafion® reveal relatively similar permeation rates. Thus, neither the PTFE nor the Nafion® membranes require substantially greater surface areas than the other to get the permeation rates to be the same. Hence, the first layer 10 can have a first surface area and the second layer 20 can have a second surface area, where the ratio of the first surface area to the second surface area can be between about 1.25:1 and about 1:1.25, or about 1:1.



Regarding the thicknesses of the membranes, thicker membranes generally mean more diffusion resistance. Regarding the porosity of the PTFE membrane, larger pores typically provide greater permeation rates. Selective membrane testing revealed that while the membrane combination having the highest permeation rate was the combination of the PTFE membrane having an average pore size of 1  $\mu\text{m}$  and the Nafion® membrane having a thickness of 25.4  $\mu\text{m}$ , the combination was structurally unstable during handling. However, the membrane combination having a higher permeation rate than the rest of the membrane combinations was the combination of the PTFE membrane having an average porosity of 0.45  $\mu\text{m}$  and the Nafion® membrane having a thickness of 50.8  $\mu\text{m}$ , even if the pore size were higher or the Nafion® thickness was smaller. In some implementations, the permeation flux rate of water vapor can be greater than  $8.0 \times 10^{-5} \text{ kg/s} \cdot \text{m}^2$ , or greater than  $1.0 \times 10^{-4} \text{ kg/s} \cdot \text{m}^2$ .

As the water vapor **40b** permeates from the Nafion® of the second layer **20**, the retained wastewater **30** can turn into residual brine solids or sludge. If the mass fraction of the wastewater is over 80% water and if most of the water is permeated through the second layer **20** of the water processing apparatus **5**, then what remains of the wastewater **30** will be mostly solid. The solid can be safely stored to facilitate ease of handling and disposal.

The water processing apparatus **5** described in FIG. 1 may be part of a containment unit for holding and treating wastewater **30**. In some implementations, such a containment unit can be a bag or inflatable bladder sealed from the ambient environment **60**. FIG. 2A show a top plan view of an example containment unit for holding and treating wastewater for water recovery. FIG. 2B shows a side view of the containment unit in FIG. 2A. The containment unit **200** can include an ionomer membrane **220** and a hydrophobic microporous membrane **210**. The ionomer membrane **220** can be a sheet that is exposed to the ambient environment outside of the containment unit **200**, and the hydrophobic microporous membrane **210** can be a sheet that forms the interior of the containment unit **200**. The sheet of the hydrophobic microporous membrane **210** can be folded over itself and the sheet of the ionomer membrane **220** can be sealed to the hydrophobic microporous membrane **210** to form a four-sided envelope. A seal **230** can be formed around the edges of the containment unit **200** to enclose the containment unit **200**. In some implementations, the containment unit **200** can be sealed using an adhesive, heat sealing, or a mechanical seal such as a clamp. The interior of the containment unit **200** may be in contact with wastewater, such as urine or brine. In some implementations, the containment unit **200** may include a receptacle **225** for receiving the wastewater. As shown in FIG. 2B, the containment unit **200** may be inflated and hold the wastewater.

In the containment unit **200**, the surface areas of the hydrophobic microporous membrane **210** and the ionomer membrane **220** can be relatively similar. The sheet of the ionomer membrane **220** can overlay and surround the sheet of the hydrophobic microporous membrane **210**. In some implementations, a surface area ratio of the hydrophobic microporous membrane **210** to the ionomer membrane **220** can be between about 1.25:1 and 1:1.25. In some implementations, the surface area ratio can be approximately 1:1. By having relatively similar surface areas, a permeation rate of the water vapor through the containment unit **200** can be optimized.

The dual membranes of the containment unit **200** form two chemically resistant layers that provide at least two

layers of protection. Additional layers or membranes can be added for increased protection. The containment unit **200** is durable, portable, and effectively encloses the wastewater inside the containment unit **200**. In some implementations, this allows for ease of handling and disposal by crew members. That way, the solids and remaining wastewater in the containment unit **200** can be safely handled and disposed of without further processing because the containment unit **200** serves as a self-containing storage.

FIG. 3 shows a schematic of various layers in an example containment unit configured to hold and treat wastewater for water recovery. FIG. 3 represents a cross-sectional schematic showing the arrangement of layers **310**, **320**, **330**, and **340** with respect to one another in the containment unit **300**. A first can include a hydrophobic microporous membrane and can be folded on itself to form the interior of the containment unit **300**. In some implementations, the hydrophobic microporous membrane can be PTFE. A second layer **320** can include an ionomer membrane and can be disposed, positioned, formed, or otherwise placed on the first layer **310**. Thus, the second layer **320** can surround the first layer **310** on all sides of the containment unit **300**. In some implementations, the ionomer membrane can be a sulfonated perfluorinated ionomer, such as Nafion®. The second layer **320** can be exposed to the ambient environment.

In order to seal the containment unit **300**, a sealing material **330** can be provided in the interior of the containment unit **300**. The sealing material **330** can be provided on the first layer **310** so that the first layer **310** can be sealed to itself. The sealing material **330** can be chemically resistant to concentrated brine in the wastewater to prevent leakage of the containment unit **300**. In some implementations, the sealing material **330** includes a thermoplastic, such as polypropylene. The polypropylene can be melted and seep into the pores of the first layer **310** so that the first layer **310** can be sealed to the second layer **320** as well. Thus, a weld can be formed in sealing the first layer **310** to itself and between the first layer **310** and the second layer **320**. The weld can be formed along the edges of the containment unit **300**. This can be shown in the seal **230** in FIGS. 2A and 2B. In some other implementations, the sealing material **330** can be an adhesive.

An outer layer **340** can be provided on the second layer **320** to provide structural support and reinforcement. The outer layer **340** can form the exterior of the containment unit **300**, while allowing the second layer **320** to still be exposed to the ambient environment. In some implementations, the outer layer **340** can include a thermoplastic, such as polyethylene. The polyethylene can strengthen the containment unit **300** so that it is less likely to tear. More specifically, the polyethylene on each side can support the layers **310**, **320** to prevent stretching when it is pressurized by fluid weight or pressure for ease of handling. The outer layer **340** can provide a third layer of protection on top of the first layer **310** and the second layer **320**. In some implementations, the outer layer **340** can be provided as netting or mesh surrounding the second layer **320** on all sides of the containment unit **300**.

From the inside to the outside, one side of the containment unit **300** includes a sealing material **330** such as smooth polypropylene netting, a first layer **310** such as PTFE, a second layer **320** such as Nafion®, and an outer layer **340** such as polyethylene netting. The other side of the containment unit **300** can be symmetrical with respect to the order of the layers **330**, **310**, **320**, and **340**. In some implementations, heat sealing or welding can seal all of the layers **330**, **310**, **320**, and **340** together around the edges to enclose the

containment unit **300**. In some other implementations, an adhesive or a mechanical seal can seal all of the layers **330**, **310**, **320**, and **340** together to enclose the containment unit **300**.

One or more containment units may be positioned in an apparatus for extracting water into a gas stream. For example, the one or more containment units can be supported in a housing structure, where the housing structure provides a dry environment for maintaining a water vapor partial pressure differential. A gas stream can flow over the one or more containment units. In some implementations, the housing structure can include materials that are liquid and gas impermeable, and also have a high chemical resistance. Some implementations of the housing structure can be made of rigid materials and some other implementations of the housing structure can be made of soft or flexible materials.

FIG. **4A** shows an example water processing apparatus including a rigid housing structure supporting containment units configured to hold and treat wastewater for water recovery. FIG. **4B** shows a schematic of the water processing apparatus of FIG. **4A**. The water processing apparatus **400** includes a containment chamber or housing structure **405**, where a first end of the housing structure **405** includes a gas inlet **410a** and a second end of the housing structure **405** includes a gas outlet **410b**. The gas inlet **410a** may be configured to receive a first gas stream into the housing structure **405**, and a gas outlet **410b** may be configured to deliver a second gas stream out of the housing structure **405**. The second gas stream includes water. In some implementations, the relative humidity of the second gas stream exiting the housing structure **405** is greater than the first gas stream entering the housing structure **405**.

The water processing apparatus **400** further includes one or more containment units **420** for holding and treating wastewater for water recovery. In some implementations, the one or more containment units **420** can be a bag or inflatable bladder. The one or more containment units **420** can include an ionomer membrane, such as Nafion®, and a hydrophobic microporous membrane, such as ePTFE. The ionomer membrane can overlay and surround the hydrophobic microporous membrane to form a membrane pair. The one or more containment units **420** may be supported inside the housing structure **405**. In some implementations, the one or more containment units **420** may be placed on a cage, platform, or other support structure **450** inside the housing structure **405**. The cage, platform, or other support structure **450** may be removable for ease of handling.

The housing structure **405** may include feedthroughs for the first and second gas streams, connections for wastewater flow, instrumentation (e.g., sensors, thermocouples, etc.), and one or more doors to insert/remove the one or more containment units **420**. As illustrated in FIG. **4B**, the one or more containment units **420** may be fluidly coupled to a wastewater inlet **415** for receiving wastewater from a wastewater supply (not shown). In some implementations, the wastewater (e.g., urine or brine) can flow from the wastewater supply and into the one or more containment units **420** via the wastewater inlet **415**. For example, a pump or compressor can meter brine into the containment units **420** from a brine storage tank.

In addition, the housing structure **405** may include instrumentation such as thermocouples for temperature control and monitoring. At least one of the thermocouples may be positioned on the one or more containment units **420** and used for feedback control for maintaining the one or more containment units **420** at a desired temperature. In some

implementations, the one or more containment units **420** are maintained at a temperature above room temperature to overcome effects of evaporative cooling. Additional thermocouples may be positioned in the housing structure **405** to monitor the temperature of the housing structure **405** and other components.

In some implementations, the housing structure **405** may include one or more doors **440** for inserting and removing the one or more containment units **420**. In some implementations, the one or more doors **440** can be made of polymethylpentene (PMP), which is a thermoplastic that is semi-transparent and chemically resistant to a variety of compounds. A fluoroelastomer (FKM) may be used as the sealing mechanism for the one or more doors **440**. In some implementations, the housing structure **405** may include feet or support components **445**. The support components **445** may provide clearance for hinges and for the one or more doors **440** to easily open. In some implementations, at least some portions of the housing structure **405** may be transparent or semi-transparent to allow for visibility for monitoring the one or more containment units **420**. In some implementations, the housing structure **405** can be made of a weldable thermoplastic, such as polyvinylidene (PVDF), which can be referred to as Kynar. PVDF exhibits excellent chemical resistance to a variety of compounds, including chromic, sulfuric, and phosphoric acid.

Other parts of the housing structure **405** may be made out of polypropylene, PVDF, PTFE sealant, and hydrophobic PTFE filters. The hydrophobic PTFE filters may be positioned in the housing structure **405** to provide containment in case of a brine leak and also to provide pressure drop for adequate flow distribution. Joints in the housing structure **405** may be sealed using PTFE to limit leakage of wastewater. It is understood that those of ordinary skill in the art may design the housing structure **405** using other materials or configurations considering issues such as design preference, cost, performance requirements, system requirements, safety requirements, available materials, technological advances, etc.

A first gas stream may flow into the housing structure **405** through the gas inlet **410a**, where the first gas stream may flow over the surfaces of each of the containment units **420**. In some implementations, the first gas stream can include air, such as room or cabin air. The first gas stream can help maintain a water vapor partial pressure differential in the housing structure **405**. When the first gas stream enters through the gas inlet **410a**, a flap **430** may divert flow of the first gas stream gas into the housing structure **405** to maintain constant flow channels while the containment units **420** deflate during drying. The flap **430** may include ePTFE and may be located at the top of the support structure **450**. The flap **430** may divert the first gas stream to a channel just above the surface of the one or more containment units **420**, maintaining velocity for mass transfer as the height of the one or more containment units **420** decreases.

After the first gas stream sweeps across the containment units **420**, the first gas stream captures water vapor and is flowed towards the gas outlet **410b**. After collecting the water vapor from the containment units **420**, the first gas stream becomes a second gas stream upon exiting the gas outlet **410b**. The second gas stream includes water, where the relative humidity of the second gas stream is greater than the relative humidity of the first gas stream. The second gas stream can be delivered to a condenser for collecting the water.

FIG. **5** shows another example water processing apparatus including a flexible housing structure supporting a contain-

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ment unit configured to hold and treat wastewater for water recovery. In FIG. 5, the water processing apparatus 500 includes a containment unit 520, where the containment unit 520 can be a bag or inflatable bladder in some implementations. The containment unit 520 can include an ionomer membrane and a hydrophobic microporous membrane. The ionomer membrane can overlay and surround the hydrophobic microporous membrane to form a membrane pair. A housing structure 505 can surround the containment unit 520 to enclose the containment unit 520, where the housing structure 505 can be made of a flexible material. The flexible material can liquid and gas impermeable. For example, the flexible material can include polypropylene or another chemically resistant plastic.

The housing structure 505 can include a gas inlet 510a and a gas outlet 510b opposite the gas inlet 510a. The gas inlet 510a may be configured to receive a first gas stream into the housing structure 505, and the gas outlet 510b may be configured to deliver a second gas stream out of the housing structure 505. The second gas stream includes water. In some implementations, the relative humidity of the second gas stream exiting the housing structure 505 is greater than the first gas stream entering the housing structure 505.

Integrated springs or support structure 530 may provide support to a flexible sheet of the housing structure 505. Rather than a rigid enclosure, the flexible sheet 505 can wrap around the support structure 530 to form the housing structure 505. The support structure 530 may provide sufficient compressive force to maintain the desired flow geometry and spacing between the flexible sheet of the housing structure 505 and the containment unit 520. The gas inlet 510a and the gas outlet 510b may direct and control flow of the first gas stream across the surface of the containment unit 520, where the first gas stream can flow between the containment unit 520 and the flexible sheet of the housing structure 505. The first gas stream can be a dry purge gas. In some implementations, as the containment unit 520 deflates, the housing structure 505 can also deflate.

After the first gas stream sweeps across the containment unit 520, the first gas stream captures water vapor and is flowed towards the gas outlet 510b. After collecting the water vapor from the containment unit 520, the first gas stream becomes a second gas stream upon exiting the gas outlet 510b. The second gas stream includes water, where the relative humidity of the second gas stream is greater than the relative humidity of the first gas stream. The second gas stream can be delivered to a condenser for collecting the water.

With respect to FIGS. 4A, 4B, and 5, the water processing apparatuses 400, 500 can be configured to provide conditions inside the housing structures 405, 505 to promote permeation of water vapor from the one or more containment units 420, 520. For example, the water processing apparatuses 400, 500 can regulate the flow of purge gas, temperature, pressure, relative humidity, and other conditions within the housing structures 405, 505. Any of the water processing apparatuses 400, 500 can include a controller (not shown) containing instructions for controlling processing conditions in the housing structures 405, 505.

The air of the first gas stream can be pre-heated to overcome the effects of evaporative cooling, and the air can be relatively dry to maintain a water vapor partial pressure differential between the containment units 420, 520 and the ambient environment. In some implementations, the air can be pre-heated above room temperature to increase the vapor pressure inside each of the containment units 420, 520,

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where room temperature can be between about 18° C. and about 30° C. For example, the temperature of the first gas stream can be heated to be greater than about 30° C. The increased temperature increases the vapor pressure to generate more vapors and gases from the wastewater in each of the containment units 420, 520. In addition, the first gas stream can be relatively dry. Typically, cabin air has a relative humidity between about 35% and about 45%. The water processing apparatuses 400, 500 can also maintain a water vapor partial pressure differential to promote permeation of water vapor inside the housing structures 405, 505. In other words, the water vapor partial pressure inside each of the containment units 420, 520 is greater than the water vapor partial pressure in the housing structures 405, 505. As the first gas stream flows across the surface of each of the containment units 420, 520, the first gas stream can transport water vapor away from the containment units 420, 520. Increasing the flow rate of the first gas stream can provide a continuously dry environment inside the housing structures 405, 505. The flow rate of the first gas stream can be adjusted depending on the surface area, performance requirements, etc. of the containment units 420, 520. By way of an example, the flow rate of the first gas stream can be between about 300 standard liters per minute (SLPM) and about 700 SLPM, such as about 500 SLPM, where the surface area of the containment unit 420, 520 is about 750 square inches and the desired water recovery from urine is about 98%.

In some implementations, the gas inlet 410a or 510a and the gas outlet 410b or 510b can passively control air flow across the containment unit 520. In particular, the housing structures 405, 505 may permit the flow of the first gas stream without any blower or heater, thereby reducing power consumption in the water processing apparatuses 400, 500. For example, the first gas stream may originate from sources within a larger apparatus, such as from an air duct in a spacecraft.

FIG. 6A shows an example schematic diagram illustrating a water processing apparatus for treating wastewater. The water processing apparatus 600a can include a housing structure 605 for containing a containment unit 620. The housing structure 605 can be similar to any of the housing structures described with respect to FIGS. 4A, 4B, and 5. The containment unit 620 can include a membrane pair of an ionomer membrane and a hydrophobic microporous membrane, as described earlier with respect to FIGS. 1-3. The containment unit 620 can be configured to hold wastewater, such as urine or brine.

A first gas stream 650a can be introduced into the housing structure 605. In some implementations, the first gas stream 650a can include cabin air originating from one or more systems of a spacecraft. The first gas stream 650a can be delivered into the housing structure 605 by a fan or blower 635, where the blower 635 can control the flow rate of the first gas stream 650a into the housing structure 605. In some implementations, the blower 635 can be equipped with a motor with a variable frequency drive to control fan speed. However, in some implementations, the water processing apparatus 600a can introduce the first gas stream 650a passively, and thereby introduce the first gas stream 650a without the aid of the blower 635.

In some implementations, the water processing apparatus 600a can include a heater 645. The heater can be utilized to heat the first gas stream 650a to above room temperature. In some implementations, the first gas stream 650a can be heated to a temperature above 30° C., or to a temperature above 50° C. The heated first gas stream 650a can enter the

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housing structure **605** to promote drying of the containment unit **620**. The heated first gas stream **650a** can heat up the temperature of the wastewater to overcome the effects of evaporative cooling, where the temperature of the wastewater can be above 30° C. However, in some implementations, the water processing apparatus **600a** does not heat up the wastewater and may introduce the first gas stream **650a** passively, and thereby introduce the first gas stream **650a** without the aid of the heater **645**.

The first gas stream **650a** can transport captured water vapor permeating from the containment unit **620** to become a second gas stream **650b**. The second gas stream **650b** exits the housing structure **605**, where the second gas stream **650b** includes water. Over time, the containment unit **620** becomes less inflated and relatively dry. In some implementations, the water of the second gas stream **650b** can enter the cabin of the spacecraft or flow directly towards a heat exchanger for collecting the water.

FIG. 6B shows an example schematic diagram illustrating the water processing apparatus of FIG. 6A integrated in a water recovery system. The water recovery system **600b** can be configured to treat wastewater and recover water. The water recovery system **600b** can include the water processing apparatus **600a**, where wastewater can be provided into the containment unit **620** of the water processing apparatus **600a** from a primary water processor **675**. The primary water processor **675** of the water recovery system **600b** can receive a first wastewater **630a** from a wastewater storage **665**, where the first wastewater **630a** can include pretreated urine. The first wastewater **630a** can be processed by the primary water processor **675** to convert the first wastewater **630a** to a second wastewater **630b**, where the second wastewater **630b** can be brine. In some implementations, the brine can be a form of concentrated urine.

After the first gas stream **650a** flows over the containment unit **620** and becomes the second gas stream **650b**, the second gas stream **650b** exits the housing structure **605**. In some implementations, the second gas stream **650b** can flow back into the cabin of the spacecraft or into a heat exchanger (e.g., condenser) for extracting the water. As illustrated in FIG. 6B, the second gas stream **650b** can become humidity condensate that can get further processed by the primary water processor **675**, and then undergo more processing in a post-processing unit **685**. After post-processing, the humidity condensate gets collected into potable water storage **695**. The potable water storage **695** can be used by crewmembers of the spacecraft.

The containment unit **620** can retain brine solids/sludge, where the ionomer membrane and hydrophobic microporous membrane serve as a barrier between the brine solids/sludge and crewmembers of the spacecraft. The containment unit **620** contains the brine solids/sludge and prevents other volatiles from entering the ambient environment. The containment unit **620** can be removed into storage into a solid waste storage unit **655**. In some implementations, the containment unit **620** can be disposed of without the need for further processing.

FIG. 7 shows a schematic diagram illustrating a water recovery system having containment units configured to hold and treat wastewater. The water recovery system **700** is configured to treat wastewater and recover water. The water recovery system **700** includes various devices, subsystems, components, sensors, and equipment for recovering water from wastewater. The water recovery system **700** includes a containment chamber or housing structure **705** for supporting a plurality of containment units **720**. The containment chamber **705** can be similar to either of the housing structure

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**405**, **505** described with respect to FIGS. 4A, 4B, and 5. Each of the containment units **720** can include a membrane pair of an ionomer membrane and a hydrophobic microporous membrane, as described earlier with respect to FIGS. 1-3.

A first gas stream **750a** can include air that can be delivered into the containment chamber **705** by a blower **735**, where the blower **735** can control the flow rate of the first gas stream **750a** into the containment chamber **705**. The water recovery system **700** can also include a heater **745** to heat the first gas stream **750a**. The heater **745** can be positioned upstream of the containment chamber **705** and utilized to heat the first gas stream **750a** above room temperature. In some implementations, the water recovery system **700** can operate passively so that the first gas stream **750a** can be introduced into the containment chamber **705** without the aid of the blower **735** or the heater **745**.

The water recovery systems **700** can also include instrumentation for monitoring or controlling conditions of the water recovery system **700**. For example, the water recovery system **700** can include sensors **760** for measuring relative humidity entering and exiting the containment chamber **705**. The relative humidity of the first gas stream **750a** entering the containment chamber **705** can be less than the relative humidity of a second gas stream **750b** exiting the containment chamber **705**. In some implementations, a desiccant can be used to dehumidify the first gas stream **750a** prior to entering the containment chamber **705**. Thermocouples **770** may be located inside the containment chamber **705** to monitor the temperature of the containment chamber **705** and the containment units **720**. At least one of the thermocouples **770** may be connected to a controller for the heater **745** to maintain the wastewater temperature. Other sensors can be used in the water recovery system **700** to measure relevant conditions of the gas streams **750a**, **750b**, such as pressure. The temperature, pressure, and relative humidity of the first gas stream **750a** entering the containment chamber **705** can be compared against the temperature, pressure, and relative humidity of the second gas stream **750b** exiting the containment chamber **705**, which can be used for evaluating the permeation rate of the containment units **720**. However, the water recovery system **700** can function without one or more of the aforementioned instrumentation. In some implementations, the conditions of the water recovery system **700** can be monitored visually.

In some implementations, the containment chamber **705** can include hydrophobic filters **780** at an inlet end and at an outlet end of the containment chamber **705**. The hydrophobic filters **780** can include PTFE or some other chemically resistant material to provide secondary containment in the event of a leak or rupture of any of the containment units **720**.

Wastewater can be injected into the one or more of the containment units **720**. In some implementations, the wastewater can be pretreated to inhibit microbial activity, minimize precipitation of solids, and limit volatilization of contaminants such as ammonia. In some implementations, the wastewater can be pre-processed to convert pretreated urine into brine. The containment units **720** are disposable and configured to be permeable to water vapor while retaining the liquid wastewater and other volatiles inside the containment units **720**. The water vapor permeation is driven by a partial pressure gradient across the permeable membrane material of the containment units **720**. The partial pressure gradient can be maintained by the flow of the first gas stream **750a**. The first gas stream **750a** flows through the containment chamber **705** to promote drying and sweeps

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permeated water vapor out of the containment chamber 705. The first gas stream 750a is humidified to become a second gas stream 750b upon exiting the containment chamber 705. The humidified second gas stream 750b is delivered to a condenser 790, where the water vapor condenses so that water can be collected and processed into potable water. In some implementations, the condenser 790 can include one or more countercurrent heat exchangers. The water in the second gas stream 750b can be condensed in the condenser 790 for collection and processing into potable water.

In some implementations, the amount of water recovered from the second gas stream 750b can be equal to or greater than about 95% of the water in the wastewater (e.g., urine). This can be true when the water processing system 700 functions as the primary water processor. However, when used as a brine processor, the amount of water recovered from the second gas stream 750b can be equal to or greater than about 80% of the water in the wastewater (e.g., brine). Thus, in some implementations, the water recovery is from pretreated urine brine. In some other implementations, the water recovery is from urine wastewater. The percentage of water recovery can be calculated using the equation: % H<sub>2</sub>O recovered=(mass H<sub>2</sub>O extracted)/(mass urine processed)×100, where the mass H<sub>2</sub>O extracted can be calculated using by taking the final mass of the containment units 720 and subtracting that from the starting mass of the containment units 720.

The recovered water can be further processed and analyzed for contaminants. For example, the recovered water can be analyzed for water quality and purity, where measurements can be taken for TOC, total dissolved solids (TDS), total coliform, and pH. For example, the recovered water can be analyzed and tested for TOC, ammonium, and pH, where the recovered water from the humidified second gas stream can have a TOC of equal to or less than about 100 mg/L, an ammonium concentration of equal to or less than about 20 ppm, and a pH between about 3 and 7. Other measurements can be taken for conductivity, acetic acid, formic acid, total inorganic carbon (TIC), and urea.

Using urine wastewater, water quality was tested after recovering water from a water recovery system as described herein. Different tests 1-7 were performed using varying chamber inlet temperatures, air flow, pressure drops, and outlet pressures. The outputs of water quality and percentage water recovery on tests 1-7 are displayed below in Table 2, where measurements of water quality were performed on the product condensate. However, water quality measurements were not available for test 1. The tests showed that the percentage water recovery was greater than 90% across all seven tests, that ammonium and pH requirements were met on all of the available tests, and that TOC requirements were met on four of the six available tests. This shows that significant contaminant reduction can be achieved using a water recovery system as described herein.

TABLE 2

Test	Total Percent H <sub>2</sub> O Recovery	TOC (ppm)	Ammonium (ppm)	pH
1	92%	—	—	—
2	95%	149	3.48	6.5
3	95%	65.8	0.25	6.7
4	91%	70.8	0.611	6.6
5	92%	48.9	2.4	6.0
6	92%	47.4	2.94	6.8
7	96%	121	2.04	7.0

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Using brine wastewater, water quality was tested after recovering water from a water recovery system as described herein. Different tests 1-2 were performed using varying temperatures, flow rates, and pressure. The different operating conditions led to different amounts of water recovery from the samples of brine. The outputs of water quality and percentage water recovery on tests 1-2 are displayed in Table 3, where measurements of water quality were performed on the product condensate. The tests showed that the percentage of water recovery was greater than 80% from brine, meaning that the total water recovery from urine was greater than 95%. The tests also showed that significant contaminant reduction can be achieved from brine using a water recovery system as described herein.

TABLE 3

Test	Total Percent H <sub>2</sub> O Recovery	TOC (ppm)	Ammonium (ppm)	pH
1	82% (97% from urine)	90.3 (after 4 days)	2.4 (after 4 days)	3.9 (after 4 days)
2	86% (98% from urine)	136 (after 9 days)	8.0 (after 9 days)	4.1 (after 9 days)

In some implementations, a water processing apparatus as described in the present disclosure using membrane technology can serve as a standalone water purification apparatus. In some implementations, the water processing apparatus as described in the present disclosure using membrane technology can be integrated in a larger water recovery architecture where the urine is pretreated in one or more subsystems. For example, the water processing apparatus can be integrated in the Environmental Control and Life Support Systems (ECLSS) of the ISS.

Although the foregoing disclosed systems, methods, apparatuses, processes, and compositions have been described in detail within the context of specific implementations for the purpose of promoting clarity and understanding, it will be apparent to one of ordinary skill in the art that there are many alternative ways of implementing foregoing implementations which are within the spirit and scope of this disclosure. Accordingly, the implementations described herein are to be viewed as illustrative of the disclosed inventive concepts rather than restrictively, and are not to be used as an impermissible basis for unduly limiting the scope of any claims eventually directed to the subject matter of this disclosure.

What is claimed is:

1. A method for treating wastewater, the method comprising:
  - a) flowing wastewater into a containment unit, wherein the containment unit comprises:
    - i) a first sheet layer forming the interior of the containment unit, wherein the first sheet layer comprises a hydrophobic microporous membrane; and
    - ii) a second sheet layer over the first sheet layer and surrounding the first sheet layer to enclose the first sheet layer, wherein the second sheet layer comprises an ionomer membrane, wherein the first sheet layer has a first surface area and the second sheet layer has a second surface area, a ratio of the first surface area to the second surface area being approximately 1:1;
  - b) treating the wastewater in the containment unit by permeating gases and vapors of the wastewater through the first sheet layer and retaining liquids and solids of the wastewater inside the first sheet layer;

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delivering a gas stream over the second sheet layer of the containment unit so that a water vapor partial pressure outside the containment unit is less than a water vapor partial pressure inside the containment unit; and collecting water vapor from the gases and vapors into the gas stream based on at least a difference between the water vapor partial pressure outside the containment unit and inside the containment unit.

2. The method of claim 1, wherein the ionomer membrane comprises Nafion®.

3. The method of claim 1, wherein the hydrophobic microporous membrane comprises polytetrafluoroethylene (PTFE).

4. The method of claim 1, wherein the first sheet layer is sealed to itself to enclose the wastewater in the first sheet layer and sealed to the second sheet layer.

5. The method of claim 4, wherein the first sheet layer is sealed to itself using one of an adhesive, heat seal, and mechanical seal, and wherein the first sheet layer sealed to the second sheet layer is sealed using one of an adhesive, heat seal, and mechanical seal.

6. The method of claim 5, wherein the first sheet layer is heat sealed by a thermoplastic material, wherein the thermoplastic material includes polypropylene.

7. The method of claim 1, further comprising: heating the delivered gas stream to a temperature greater than about 30° C.

8. The method of claim 1 further comprising: condensing the collected water vapor into potable water.

9. The method of claim 1, wherein treating the wastewater in the containment unit comprises:

holding the liquids and solids of the wastewater inside the first sheet layer;

permeating the gases and vapors of the wastewater through the first sheet layer; and

selectively permeating water vapor of the gases and vapors through the second sheet layer but substantially blocking contaminants of the gases and vapors at the second sheet layer, wherein the second sheet layer is exposed to the gas stream.

10. The method of claim 1, wherein a thickness of the second sheet layer is at least 50.8 µm.

11. The method of claim 1, wherein the water vapor is collected at a rate of greater than about  $8.0 \times 10^{-5}$  kg/s·m<sup>2</sup>.

12. The method of claim 1, wherein the containment unit further comprises:

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a third sheet layer over the second sheet layer and forming the exterior of the containment unit, wherein the third sheet layer comprises polyethylene.

13. The method of claim 1, wherein the wastewater comprises one of urine and brine.

14. A method of manufacturing a containment unit for treating wastewater, the method comprising:

providing a first sheet layer having a first surface area, wherein the first sheet layer comprises a hydrophobic microporous membrane;

sealing the first sheet layer to itself to form an interior of the containment unit, wherein the first sheet layer is configured to enclose wastewater in the first sheet layer;

providing a second sheet layer having a second surface area over the first sheet layer and surrounding the first sheet layer, wherein the second sheet layer comprises an ionomer membrane, wherein the second sheet layer is exposed to the ambient environment; and

sealing the first sheet layer to the second sheet layer, wherein a ratio of the first surface area to the second surface area is approximately 1:1.

15. The method of claim 14, wherein the ionomer membrane comprises Nafion®.

16. The method of claim 14, wherein the hydrophobic microporous membrane comprises polytetrafluoroethylene (PTFE).

17. The method of claim 14, wherein sealing the first sheet layer to itself comprises using one of an adhesive, heat seal, and mechanical seal, and wherein sealing the first sheet layer to the second sheet layer comprises using one of an adhesive, heat seal, and mechanical seal.

18. The method of claim 14, further comprising:

providing a third sheet layer over the second sheet layer to form an exterior of the containment unit, wherein the third sheet layer comprises polyethylene.

19. The method of claim 14, wherein a thickness of the second sheet layer is at least 50.8 µm.

20. The method of claim 14, wherein the first sheet layer is impermeable to liquids and solids of the wastewater but permeable to gases and vapors of the wastewater, and wherein the second sheet layer is permeable to water vapor and impermeable to one or more contaminants of the gases and vapors.

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